The Status of the Constellation-X Mission

Robert Petre[*1], Nicholas E. White[2], Harvey Tananbaum[3], Ann Hornschemeier[1], Jay Bookbinder[3], Michael Garcia[3], Jean Grady[4], Caroline Kilbourne[1]
[1]X-ray Astrophysics Laboratory, Code 662, NASA / GSFC, Greenbelt, MD 20771 USA
[2]Astrophysics Science Division, Code 660, NASA / GSFC, Greenbelt, MD 20771 USA
[3]Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138 USA
[4]Constellation-X Project Office, Code 445, NASA / GSFC, Greenbelt, MD 20771 USA

ABSTRACT

The Constellation-X mission will address questions central to the NASA Beyond Einstein Program, using high throughput X-ray spectroscopy to measure the effects of strong gravity close to the event horizon of black holes, study the formation and evolution of clusters of galaxies to precisely determine cosmological parameter values, measure the properties of the Warm-Hot Intergalactic Medium, and determine the equation of state of neutron stars. Achieving these science goals requires a factor of ~100 increase in sensitivity for high resolution spectroscopy over current X-ray observatories. This paper briefly describes the Constellation-X mission, summarizes its basic performance parameters such as effective area and spectral resolution, and gives a general update on the mission. The details of the updated mission configuration, compatible with a single Atlas-V 551 launch vehicle, are presented.

Keywords: Constellation-X, X-rays, black holes, dark energy

1. INTRODUCTION

Constellation-X is NASA's next major X-ray astronomy mission. Along with LISA, it is a flagship mission of NASA's Beyond Einstein program. Constellation-X is to provide a substantial improvement in sensitivity for X-ray spectroscopy, that will lead to revolutionary advances in our understanding of the physics in regions of high gravity (black holes and neutron stars) and of the major constituents of the universe (dark energy, dark matter, and the missing baryons). The mission is approved, and is currently in a pre-phase A study phase, involving definition of its scientific objectives and derived mission requirements, mission configuration studies, and development of mission enabling technology. Constellation-X is the next major NASA astrophysics observatory after JWST (2013 launch), based on its ranking in the 2000 Decadal survey. Significant funding is anticipated to start around 2009/2010, making 2017/18 the earliest realistic launch date.

Over the past year, both the scientific goals and the mission requirements of Constellation-X have been thouroughly reassessed. The motivation for this exercise was two-fold. First was the response by the Constellation-X program to requests for information from the Beyond Einstein Program Assessment Committee (BEPAC). This committee was convened by the National Academy of Sciences at NASA's request to assess the five Beyond Einstein missions on the basis of potential scientific impact, and realism of technology and management plans and cost estimates, and recommend which of the five should be launched first. The second motivation was an investigation whether the mission objectives could be accomplished using a more cost effective launch vehicle (an Atlas V 551 instead of a Delta IV H). The result of the reassessment was largely an affirmation of the existing scientific objectives. Some of the mission requirements were refined, however, leading to changes in some instrument performance specifications. The plausibility of these changes was in turn based on continued progress in the technology development of mirrors and detectors.

This paper represents a snapshot of Constellation-X: its scientific objectives, the required performance, the current mission configuration, and the status of mirror and detector technology development. These topics are covered in the sections below. Of particular note are the revised instrument performance requirements: field of view (now 5 arc

[*] robert.petre-1@nasa.gov; phone 301-286-3844; fax 301-286-0677

UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XV, edited by Oswald H. W. Siegmund
Proc. of SPIE Vol. 6686, 66860B, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.734379

minutes instead of 2.5 arc minutes), spectral resolution ($E/\Delta E$) in the 0.3-1.0 keV band (now ≥1250, compared with the previous ≥300), and high-energy effective area (now ≥150 cm^2 at 40 keV, compared with 1500 cm^2). These changes, and all the performance requirements, derive directly from the driving scientific objectives that are summarized in the next section.

2. SCIENCE OBJECTIVES

Constellation-X has four driving scientific objectives; objectives that define the key mission requirements. These are:

- Using black holes to test General Relativity (GR) and measuring black hole spin.
- Improving the constraints on the key Dark Energy (DE) parameters by a factor of ten using observations of clusters of galaxies.
- Unambiguous detection of the hot phase of the Warm-Hot Intergalactic Medium (WHIM) at $z > 0$.
- Measuring the mass-radius relation of neutron stars to determine the Equation of State (EOS) of ultra-dense matter.

2.1 Black Holes

The matter spiraling into black holes provides a direct probe of strong field gravity. This has been demonstrated by the detection of relativistically broadened iron K lines from supermassive and stellar mass black holes. The profiles of these lines provide a measure of the black hole spin. Current observation times to resolve detailed profiles are typically 1 day, compared to orbital timescales of an hour for a 10^7 solar mass black hole. Further progress toward testing the predictions of GR requires a large collecting and high spectral resolution, as provided by Constellation-X. Using Constellation-X, it will be possible to track with time the flux and energy behavior of individual clumps of matter as they spiral toward the event horizon. The temporal behavior will be used to map the gravitational field and calculate the mass and spin of the black hole. If GR is correct, then the inferred black hole properties should be consistent from clump to clump and for the same clump at different radii.

2.2 Dark Energy

Clusters of galaxies can be used to constrain Dark Energy in two ways: (i.) they are "standard candles" through gas mass fraction (f_{gas}) and Sunyaev-Zeldovich effect distance measures, and (ii.) their evolution is very sensitive to cosmology. The clusters to be used for both types of experiment are the most dynamically relaxed, highly X-ray luminous clusters spanning the redshift range $0 < z < 2$. A sample of several hundred such clusters can be observed with sufficient sensitivity by Constellation-X in ~10 million seconds. Simulations indicate that if f_{gas}, the fraction of gas mass to total mass, which is derivable entirely from the X-ray observations, is measured to 5 percent or better for each of 500 galaxy clusters and then used as a standard ruler, extremely tight constraints can be obtained on values for cosmological parameters (e.g., Ω_M is constrained to ≤0.01, Ω_Λ to ≤ 0.05). A cross check to the f_{gas} results with similar accuracy is provided by the absolute distance measurements obtained by combining the X-ray measurements with sub-mm measurements of the Sunyaev-Zeldovich effect for this same set of clusters. Additionally, determining the evolution of the cluster mass function with redshift reveals the growth of structure and provides a powerful independent measure of cosmological parameters.

2.3 Missing Baryons

Current theory predicts that most of the baryonic matter in the low redshift universe is concentrated in the Warm-Hot Intergalactic Medium (WHIM), a web of filaments between mass concentrations (i.e., clusters of galaxies) with density of ~10^{-4}-10^{-5} cm^{-3} and temperature 10^5-10^7 K. The low density makes these filaments extremely challenging to detect directly. The most straightforward way of detecting them and measuring their density and distance is through the O VII and O VIII absorption lines they produce upon background continuum sources, such as AGN. Absorption lines created by the WHIM are in the low opacity limit, so the equivalent width of the lines translates directly into a column density equal to the average ion density multiplied by the depth of the filament, providing a prime measure for the mass content of the hot gas. Measurement of the filament redshifts locates them in the Cosmic Web connecting all groups and clusters, and determination of the turbulent widths of the lines measures the gravitational shocks, and galactic superwinds that heat the WHIM. These measurements can only be performed with high spectral resolution ($E/\Delta E >$ 1000) and large collecting area as provided by Constellation-X.

2.4 Neutron Star Equation of State

Neutron stars in binary systems offer several possible means of measuring the neutron star mass-radius relation, from which the equation of state can be inferred. (i.) A continuous supply of fresh metals onto the surface leads to the likely formation of a detectable absorption line spectrum. The gravitational redshift of these lines provides a direct measure of M/R. (ii.) Accretion also leads to thermonuclear X-ray bursts; brief but bright flashes of thermal X-ray radiation shining through the neutron star atmosphere, during which the spin rate of the neutron star can be observed directly (burst oscillations). Both the amplitude and shape of these pulsations encodes mass and radius information. For example, the modulation amplitude is influenced by gravitational light deflection in the strong gravitational field of the neutron star, which depends directly on the compactness. Fitting of the observed pulses to a physical model of surface emission from a rotating neutron star can provide constraints on the stellar mass and radius. Constellation-X will be the first X-ray observatory with the capability of making the sensitive high spectral resolution measurements required for both approaches and simultaneously fast timing measurements of X-ray bursts for the second.

2.5 Additional Objectives

Meeting these four primary objectives requires a substantial increase in capabilities over existing X-ray observatories. These new capabilities will enable Constellation-X to produce major advances covering all of astrophysics from solar system objects to distant quasars. Prominent ones include:

- Constellation-X will provide direct astrophysical insight into the evolution of the environment around accreting massive black holes by exploring changes in the X-ray spectral shape and components of luminous AGN out to and beyond $z \sim 6$.

- Constellation-X will provide unique insight into “cosmic feedback,” the interaction between AGN and their environments, by simultaneously determining the effects of the AGN on surrounding gas (e.g., groups and clusters) as a function of redshift, measuring the energy input from star formation (e.g., superwinds), and measuring the IGM metallicity as a function of redshift.

- Constellation-X will produce the accurate surface brightness and temperature profiles of clusters of galaxies beyond the virial radius, allowing a direct measurement of the amount and distribution of dark matter to an unprecedented level of precision. Accurate comparisons can be made with weak and strong lensing mass measurements and determinations of the gas content via the Sunyaev-Zeldovich effect.

- Constellation-X will determine the prevalence of supermassive black hole binary systems in the centers of galaxies by resolving Fe-K lines of the binary component objects.

3. OBSERVATORY REQUIREMENTS

The four driving scientific objectives have been used to define the observatory performance requirements. The main requirements are listed in Table 1, along with the driving scientific objectives. As the scientific objectives are refined, so are the requirements. Several significant changes are worth noting. The need for accurate cluster surface brightness and temperature profiles to large radii has led to an increase in the minimum field of view from 2.5 arc minutes to 5 arc minutes. Performing absorption spectroscopy to an accuracy allowing determination of WHIM properties requires a spectral resolution of 1250 in the 0.3—1.0 keV band. The required angular resolution to meet the driving objectives is 15 arc seconds (half power diameter), though higher angular resolution will make fulfillment of some of these objectives easier.

Table 1. Constellation-X performance requirements, as driven by science objectives.

Constellation-X Performance Requirements			
Bandpass		0.25-10.0 keV	
Effective Area			
	@1.25 keV	15,000 cm^2	Black hole spin evolution with time, dark energy using 500 clusters of galaxies
	@6.0 keV	6,000 cm^2	Black hole GR tests
	@40 keV	150 cm^2	Black hole GR tests
Angular resolution			
	0.3-7 keV	15" HPD	Dark energy using clusters, missing baryons
		5" HPD goal	Consistent with observatory HPD goal of 5 arc seconds
	7-40 keV	30" HPD	Black hole GR tests
Spectral resolution			
	0.3-1 keV	$E/\Delta E = 1250$	Missing baryons using many 10's of background AGNs
	6 keV	$E/\Delta E = 2400$	Dark energy using clusters of galaxies
Field of view		5 x 5 arc min	Dark energy using clusters of galaxies
		5 x 5 arc min goal	
Count rate		10^3 cts/sec/pixel	Neutron star equation of state

4. MISSION IMPLEMENTATION

The planned implementation of Constellation-X has changed substantially in response to two stimuli: the revised scientific objectives and derived performance requirements, and the need to minimize mission cost. The cost issue has led to a redesign of the mission configuration, based on the use of the Atlas V 551 as the launch vehicle.

The current Constellation-X configuration consists of a single spacecraft. The core instrumentation consists of four identical Spectroscopy X-ray Telescopes (SXTs). Each SXT consists of a Flight Mirror Assembly (FMA) and an X-ray Microcalorimeter Spectrometer (XMS). The four identical telescopes ensure mission success even with the loss of one detector, through longer exposures.

The FMA has been redesigned to fit within the Atlas V envelope while still satisfying performance requirements.[1] Each FMA unit has a 1.3 m diameter and a 10 m focal length. It has 168 nested Wolter I shells. The mirrors are constructed from glass sheets, with 20 cm azimuthal length and 400 μm thickness. Optical figure is imparted to the sheets by thermal forming. Each mirror shell consists of a set of identical azimuthal segments, with separate primary and secondary reflection stages. The inner 63 shells are divided into five segment pairs, the outer 105 into ten pairs. The large number of modestly sized segments is intended to make the mirrors amenable to mass production patterned after that used for the ASCA and Suzaku mirrors. Their manageable size simplifies manufacture, assembly, integration, and testing. (For instance, the 1.3 m aperture can be fully illuminated in the X-ray Calibration Facility at NASA Marshall Space Flight Center.)

The XMS is a cryogenically-cooled microcalorimeter array. The baseline technology incorporates Transition Edge Sensor (TES) arrays.[2] The baseline focal plane layout incorporates a 32x32 pixel array providing high spectral resolution covering the central 2.5 arc minutes, and the outer portion of the field of view covered by position sensitive TES detectors with slightly reduced spectral resolution. Each focal plane detector will be kept at a temperature of 50 mK by a multistage cryogen-free refrigerator.

Complementing the SXTs are high and low energy spectrometers, the Hard X-ray Telescope (HXT) and the X-ray Grating Spectrometer (XGS). The HXT provides modest area, spectral resolution and angular resolution to allow measurements of continua from bright sources up to 40 keV. Possible implementations include one or two stand alone mirror-detector systems or augmentation of the energy response of inner SXT mirrors using multilayers. At low energy, the XGS provides high resolution ($E/\Delta E \geq 1250$) and modest collecting area (≥ 1000 cm^2) in the 0.3-1.0 keV band. Possible implementations include either fixed or removable transmission or reflection gratings in the light path of one or two of the SXTs. The specific implementation of these two instruments depends upon what is selected by NASA in an open competition.

Figure 1 displays the effective area of Constellation-X as a function of energy. The effective area plot shows the two orders of magnitude improvement offered by Constellation-X over existing high resolution spectrometers on XMM-Newton and Chandra. Figure 2 shows the spectral capabilities of Constellation-X as a function of energy. The left plot shows the improvement in all energy bands over existing spectrometers. The plot for the XGS is representative of suggested designs. The right plot compares the Constellation-X spectral resolution with the resolution needed to resolve specific kinds of spectral features. The spectral resolution makes accessible a substantial number of new spectral diagnostics across the X-ray band.

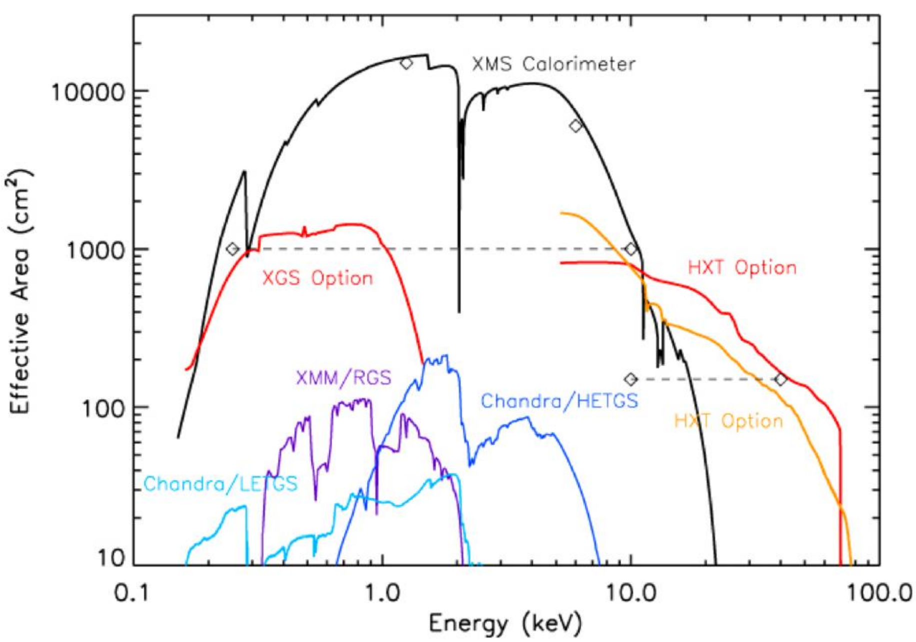

Figure 1: The effective area of Constellation-X as a function of energy. Also plotted are the effective area of current high resolution spectrometers. Constellation-X offers an increase in collecting area of two orders of magnitude over most of its band.

Figure 3 shows a cutaway view of the Constellation-X observatory (with thermal insulation removed) with the major components labeled. The Atlas V 551 fairing is large enough to allow a fixed optical bench. The observatory is modular, with a mirror system module, a spacecraft module a metering structure/optical bench, and a focal plane module. The only deployables are the solar panels, the mirror covers, and the mirror sunshade. The avionics requirements are met by existing, off the shelf components. Figure 4 shows the observatory deployed, and in its launch configuration.

Constellation-X will be launched directly into a 700,000 km radius halo orbit around the sun-earth L2 point. This orbit provides a thermally stable environment, and keeps the spacecraft within the earth's magnetosheath to minimize particle background. The orbit also affords high operational efficiency, with uninterrupted viewing of sources within the field of regard. The field of regard is 360-degree band with a width of ±20 degrees off the normal plane to the spacecraft-sun direction; any location in the sky is accessible for 5 weeks or more every six months. The mission is being designed to have a 5-year life, but will carry sufficient consumables (propellant for orbit correction) for a 10-year life.

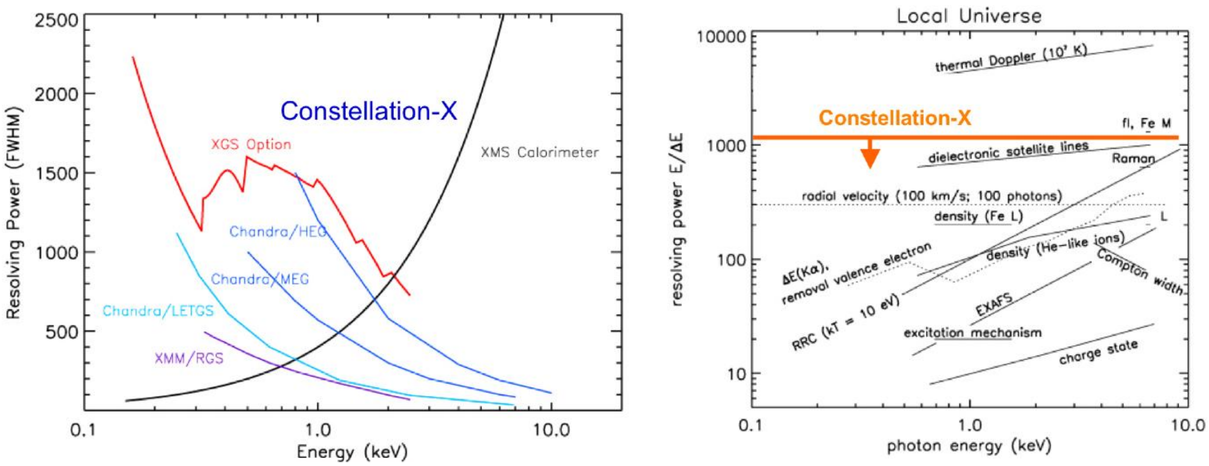

Figure 2: (left) The spectral resolving power of Constellation-X as a function of energy. Also plotted are the resolution curves for current high resolution spectrometers. (right) The Constellation-X energy band contains the K-line transitions of 25 elements Carbon through Zinc allowing simultaneous direct abundance determinations using line-to-continuum ratios, plasma diagnostics and at iron K bulk velocities of 200 km/s or better.

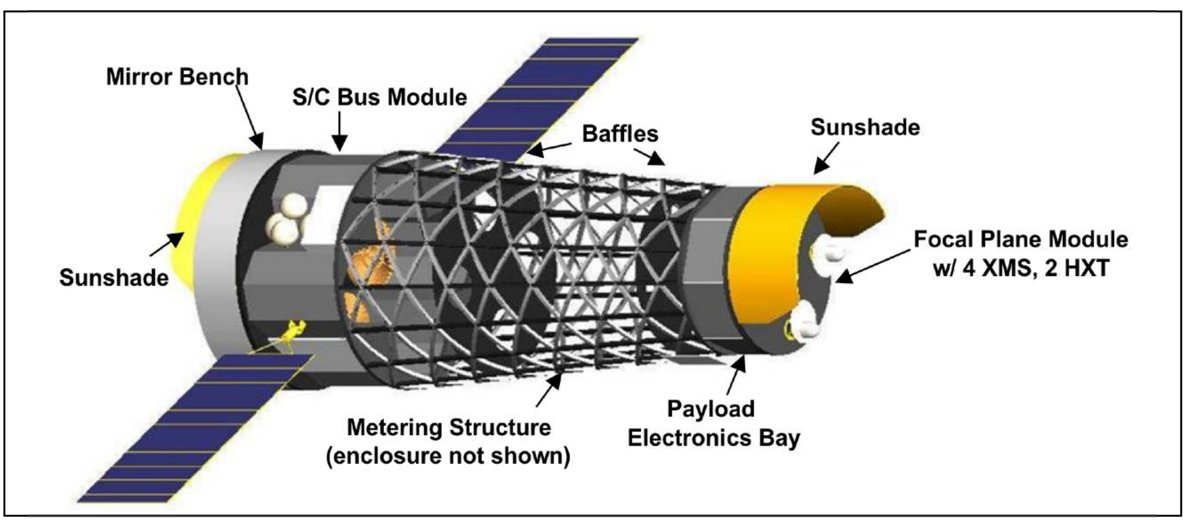

Figure 3: The current Constellation-X configuration. The covering of the truss structure is not shown.

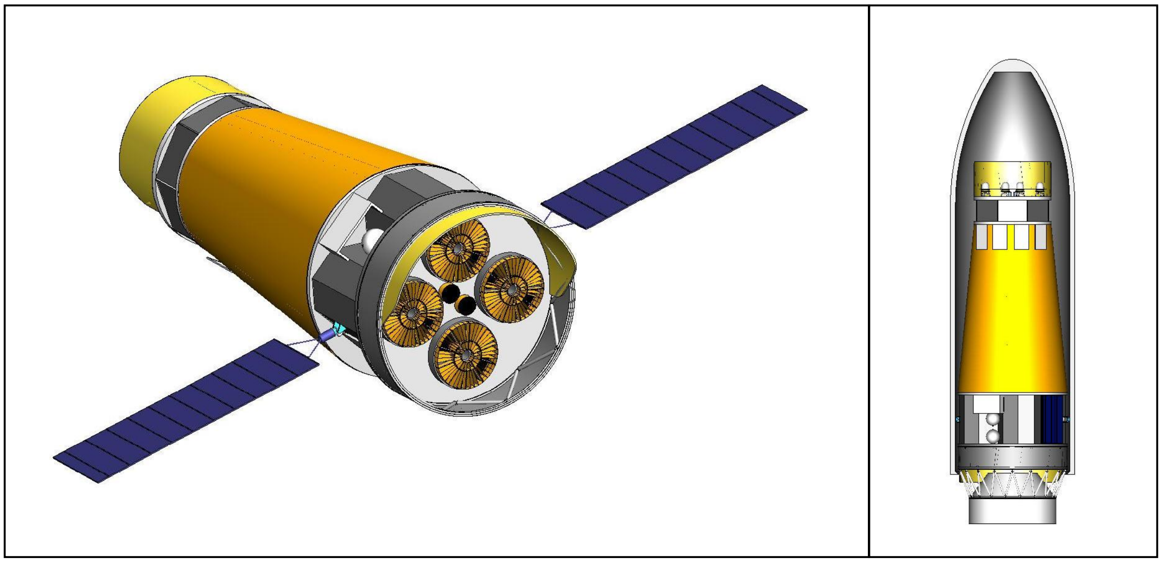

Figure 4: The Constellation-X observatory, deployed (left) and in launch configuration in an Atlas V 551 fairing (right). The deployed configuration shows the four 1.3 m diameter SXT mirrors.

5. TECHNOLOGY DEVELOPMENT

The Constellation-X project has supported development of enabling technology for the mirrors and detectors. The technology development program consists of developing the most crucial technology items for meeting the mission requirements. This has primarily been the SXT mirrors and the XMS. Despite modest funding, significant progress has been made in each area.

5.1 Mirrors

Mirror technology development has focused on the basic components: how to form glass mirror substrates that meet the figure and roughness requirements, how to measure their surface properties on all relevant spatial scales, how to align them to meet the system angular resolution requirement, and how to mount them without imparting distortions to the optical surface. The status of these various aspects of mirror technology development is summarized in other presentations at this conference.[3-8]

As shown in Figure 5, substantial improvement has been made in the heat forming process. It is now possible to form mirror segments meeting the angular resolution requirement. Progress has been made in other areas of mirror development as well. Metrology methods have been introduced that allow accurate two-dimensional substrate surface mounting on various scales, repeatable measurement of axial power spectral distributions, and image quality after one or two grazing-incidence reflections. The ability to align a pair of segments and temporarily mount them to a holding fixture has been demonstrated. Experiments leading to a means for permanently mounting aligned segments are underway.

5.2 Detectors

Calorimeter arrays fabricated at Goddard using superconducting transition-edge sensors (TES) have demonstrated the ability to meet the Constellation-X XMS requirements for spectral resolution, quantum efficiency, and pixel size in a close-packed geometry.[2] Breakthrough energy resolution has been achieved with sensors employing electroplated all-gold and gold/bismuth X-ray absorbers. Resolutions at 6 keV for 13 pixels with Au absorbers have ranged from 2.3 to 3.1 eV. Resolution as good as 2.1 eV at 6 keV has been measured with a pixel with a Au/Bi absorber, and the result improves to 1.8 eV with data screening based on the temperature of the TES prior to X-ray absorption (Figure 5). These results have been enabled by cantilevered absorbers that make contact to the TES only in regions that are not part of the active thermometer. With this approach, rapid thermalization of the X-ray energy is achieved and interaction between the absorber and TES sensor films is avoided. This design enables a uniform high performance and is compatible with large-format, high fill-factor arrays.

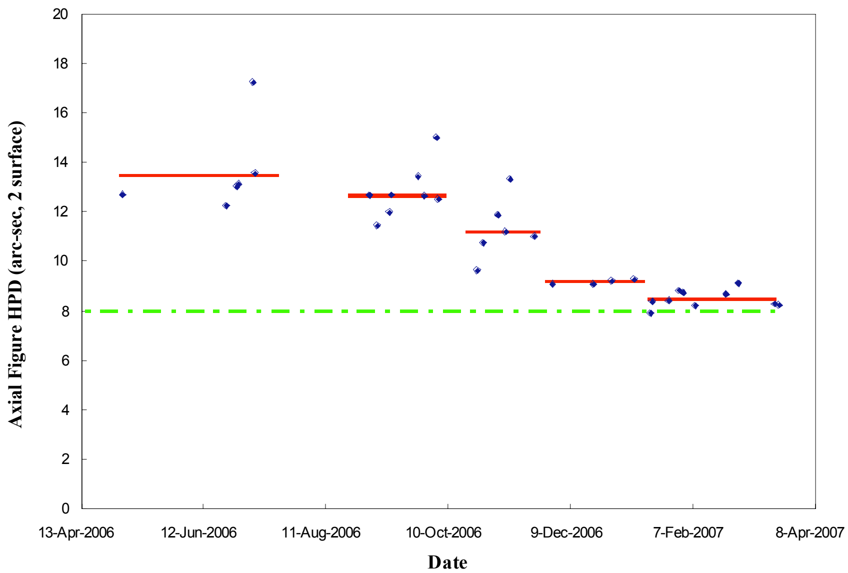

Figure 5: Mirror segment forming process improvements introduced over the past year have led to consistent improvement in segment performance, as indicated by the axial figure half-power diameter (HPD). The most recently produced segments are approaching the performance requirement, indicated by the green dashed line.

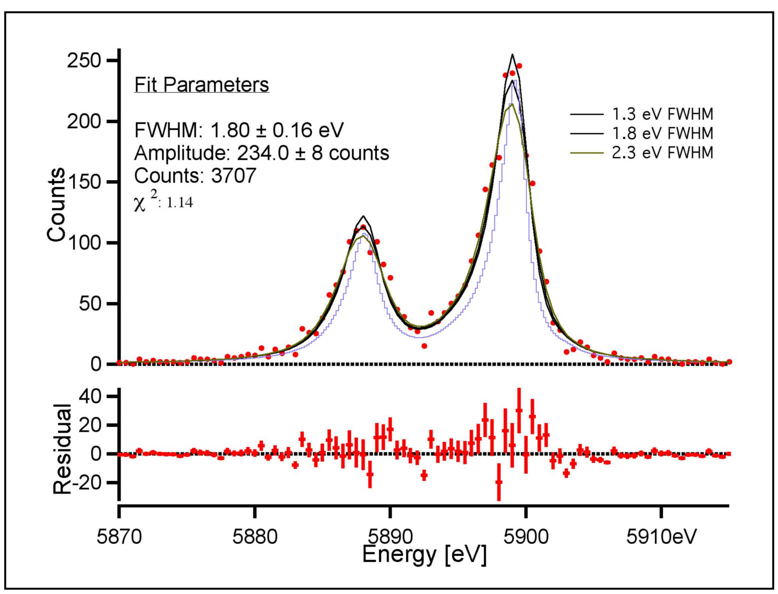

Figure 6: A recently-obtained spectrum of the Mn Kα line from a Fe^{55} source using a TES calorimeter. The spectral resolution is approximately 1.8 eV at 5.9 keV.

The electronics for reading out the XMS focal plane array have also progressed considerably. Superconducting multiplexers developed and implemented at NIST – Boulder can now read 128 X-ray TES pixels using only 4 SQUID amplifiers. This N x 32 multiplexing is the same scale needed for the XMS, but the system bandwidth is currently about a factor of four lower than will ultimately be achieved by the flight electronics.

6. SUMMARY

As NASA's next major astrophysics observatory, Constellation-X opens the window of X-ray spectroscopy with a two orders of magnitude gain in capability over current missions. The science objectives driving the need for this new capability are precision tests of GR in the strong field limit and precision cosmology. The reassessment of the these objectives undertaken over the past year has led to their reaffirmation, along with a refinement of the performance requirements. These revised requirements in turn have led to a configuration compatible with a more cost-effective launch vehicle. Progress continues in the key mission-enabling technology development. Overall, the Constellation-X mission proves to be a scientifically robust, technically feasible mission within the reach of current capabilities. Constellation-X is a Great Observatory that will enable a broad range of science, engaging a large user community.

REFERENCES

[1] P. B. Reid, M. Freeman, and T. T. Saha, "New Design for the Constellation-X Spectroscopy X-ray Telescope (SXT)," Proc. SPIE, 6688-8 (2007).

[2] S. R. Bandler, et al. "Uniform High-Spectral Resolution Demonstrated in Arrays of TES X-ray Microcalorimeters," Proc. SPIE, 6686-5 (2007).

[3] W. W. Zhang, et al., "Constellation-X Mirror Technology development Status and Plan," Proc. SPIE, 6688-1 (2007).

[4] W. W. Zhang, et al., "Fabrication of Mirror Segments for the Constellation-X Mission," Proc. SPIE, 6688-29 (2007).

[5] J. P. Lehan, et al., "Toward a Complete Metrologic solution for the Mirrors for the Constellation-X Spectroscopy X-ray Telescope," Proc. SPIE, 6688-35 (2007).

[6] J. P. Lehan, et al., "Testing of the Mirrors for the Constellation-X Spectroscopy X-ray Telescope with a Refractive Null," Proc. SPIE, 6688-36 (2007).

[7] T. J. Hadjimichael, et al., "Alignment and Integration Techniques for Mirror Segment Pairs on the Constellation-X Telescope," Proc. SPIE, 6686-38 (2007).

[8] K.-W. Chan, et al. "Mechanical and Thermal Analysis of the Spectroscopy X-ray Telescopes for the Constellation-X Mission," Proc. SPIE, 6688-39 (2007).